

EXPLORING OPPORTUNITIES AND LIMITATIONS OF 3D CONCRETE PRINTING TECHNOLOGY IN NEW ZEALAND

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SUMMARY

3D printing, formally known as additive manufacturing (AM), is a process by which physical objects are created by depositing materials in layers based on a digital model with no needs of tooling and little human intervention. 3D concrete printing is an alternative construction method which has the potential to revolutionize the construction industry globally, including New Zealand, with significant benefits such as reduced manpower; greater geometric freedom; reduced material consumption and wastage; improved accuracy and safety on-site. The potential benefits of this technology could affect housing affordability and address current needs in the New Zealand housing market. This paper analyses potential opportunities and challenges of 3D concrete printing for New Zealand's housing market. First, a comprehensive review of state-of-art 3D concrete printing technologies is presented. Then, a case study is used to show the benefits and limitations of 3D printing technique in the New Zealand context. Preliminary results suggest that if the full potential of 3D printing technology can be realised, the productivity of the construction industry and the affordability of houses in New Zealand can be improved. Finally, the paper suggests the future research required to make 3D printing a feasible construction technique in New Zealand.

INTRODUCTION

The building construction industry in New Zealand has long been criticized for its conservatism and lack of innovation (Buckett, 2013). As a consequence, the industry's productivity cannot meet the demand. At the same time, New Zealand is facing a housing crisis (Johnson, 2018), particularly in the Auckland region where an accumulated shortfall of 20,043 homes has built up over the last four years as shown in Table 1 (Stats NZ, 2019). The under-supply of housing is contributing to high house prices which will impact people's ability to enjoy adequate living standards (Ministry of Business, Innovation & Employment, 2017). An unknown number of children is living in cars and thousands more are hospitalized for preventable illnesses caused by poor housing (Johnson, 2018).

In this regard, 3D printing seems to be a promising solution that can fabricate buildings with less construction time, cost and human resources when compared to traditional construction. This paper aims to briefly explore opportunities and limitations of this technology in the New Zealand context.

Table 1 Auckland's Growing Housing Shortage

Year at 30 th June	Natural increase in population*	Net migration*	Total increase in population	Estimated No. of new dwellings needed	No. of new dwellings consented*	Annual housing shortfall	Cumulative housing shortfall
2014	14,200	19,600	33,800	11,267	6,873	4,394	4,394
2015	13,900	29,100	43,000	14,333	8,300	6,033	10,427
2016	13,800	30,800	44,600	14,867	9,651	5,216	15,643
2017	13,800	28,900	42,700	14,233	10,364	3,869	19,512
2018	13,000	25,700	38,700	12,900	12,369	531	20,043

* Source from NZ Statistics (Stats NZ, 2019)

STATE-OF-THE-ART TECHNOLOGIES FOR 3D CONCRETE PRINTING

The state-of-the-art 3D concrete printing technologies and their related advantages and limitations are discussed in this section. 3D concrete printing technology can be categorized into three main techniques, namely Material Deposition Method (MDM), Binder jetting and Smart Dynamic Casting.

Material Deposition Method

The material deposition method (MDM) is an extrusion-based process that successively lays one layer of material on top of the other according to a digital model (Panda, Bahubalendruni, Biswal, & Leite, 2017). Popular MDM techniques such as contour crafting, concrete printing and mesh mould used in 3D concrete printing are described below.

Contour Crafting

Contour crafting (CC) is a leading onsite concrete printing method patented by Prof. Behrokh Khoshnevis at the University of Southern California in 2004 (Khoshnevis B. , 2004). Unique to CC is the use of trowels which are controlled by a computer to create smooth, accurate and free-form surfaces (Khoshnevis, Russell, Kwon, & Bukkapatnam, 2001). In CC, a nozzle attached to a gantry system is moved back and forth to automatically build a house in a single run (Figure 1). The distinctive advantages of CC, compared with other material deposition methods, are better surface quality, higher fabrication speed and the ability to use in-situ resources (Khoshnevis B. , 2004). Houses built with this technology can be used as low-income housing and emergency shelter immediately after construction.

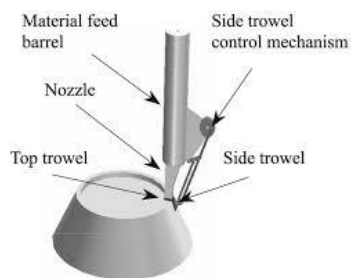


Figure 1 Contour crafting process with a unique trowel attached to the nozzle (Khoshnevis B. , 2004)

Concrete Printing

Concrete Printing technology is developed by the research team led by Dr. Richard Buswell at the Loughborough University in UK (Loughborough University, 2019). The setup of the printing system includes a 5.4m (L) x 4.4m (W) x 5.4m (H) gantry printer (Figure 2a). The computer-controlled 3D concrete printer precisely deposits successive layers of high-performance

concrete to create complex structural components (Figure 2b). More recently, this team developed a new technique namely “Curved-layered Printing”, which improves the aesthetic and mechanical properties of a printed part without the need for complex moulding systems (Lim, et al., 2016)

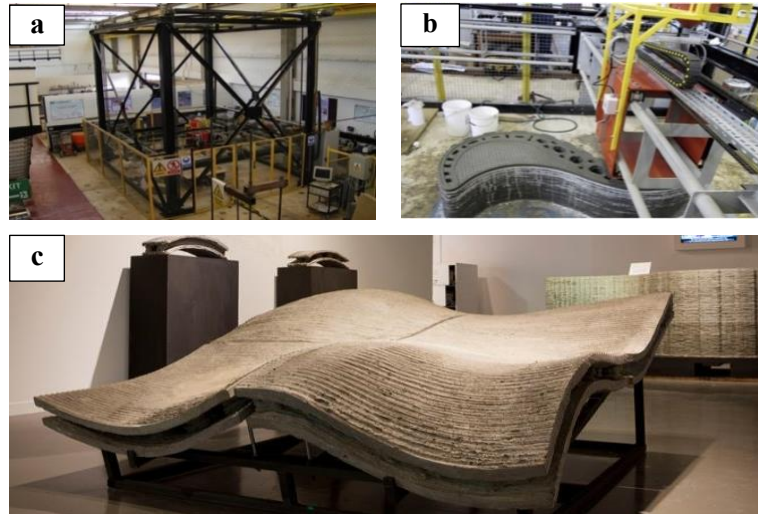


Figure 2 (a) The printing frame of Concrete Printing (Lim S. , et al., 2011); (b) The printing process (Lim, et al., 2009); (c) Double-curved concrete cladding panel cast with voids and slots for posting-tensioning (Chua & Leong, 2017).

Mesh Mould

From 2015 to 2018, the Swiss Federal Institute of Technology (ETH) in Zurich developed the Mesh Mould technology to investigate the integration of structural reinforcement and concrete formwork into a single robotically fabricated material system (Gramazio Kohler Research, 2018). The reinforcement mesh is formed by layers of long wires that are robotically bent, welded, and cut either onsite or in a prefabricated environment. Concrete is then poured over this porous formwork and later finished with a cover layer manually to form a structural element (Hack, et al., 2017). This technology presents a number of advantages such as reduced time for fabricating complex structures, the integration of reinforcement, the absence of cold joints and the ability to produce meshes in situ (Wangler, et al., 2016).



Figure 3 Mesh mould process (Hack, et al., 2017): (a) Robot extruding a 1:1 scale prototype; (b) Filling and vibrating process; (c) Half-filled with concrete.

Binder jetting

The binder jetting, also known as inkjet printing, is a 3D printing process that creates objects by depositing the binder layer by layer over a powder bed and remove the unbonded material to reveal the final objects (Tay, et al., 2017). The representative in this field is D-Shape, invented, developed and patented by Italian engineer Enrico Dini (D-shape, 2019). The outstanding advantages of this technology include the high degree of geometric freedom and a higher resolution (high surface quality) (Richardson, 2017). On the other hand, this

manufacturing technique requires longer printing time when compared to other concrete printing techniques, and it is difficult to use in situ (Wangler, et al., 2016). It also requires extensive post-processing to remove the excess deposition powder (Richardson, 2017). The binder jetting is still in its infancy and the first one-shot-printed house using this technology was built in 2010 (Figure 4).

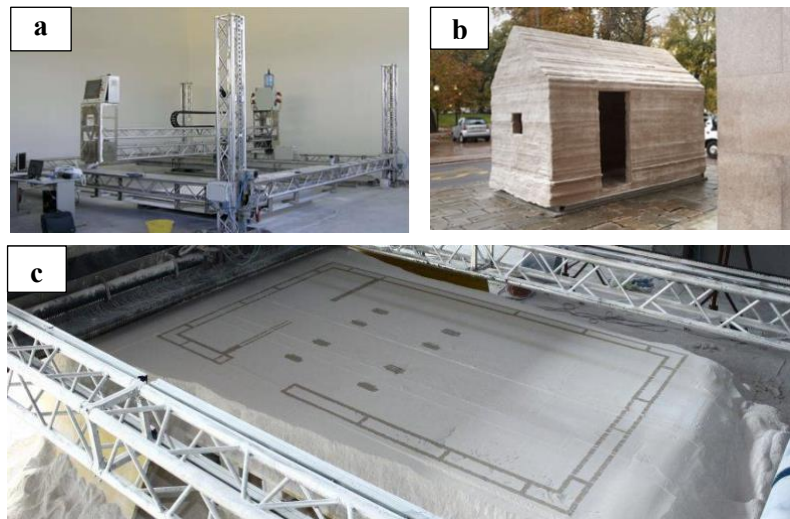


Figure 4 (D-Shape, 2010): (a) The D-Shape printing machine; (b) The first one-shot-printed house by D-Shape technique; (c) The printing process.

Smart Dynamic Casting

Smart Dynamic Casting is a new concrete construction technique developed at the ETH Zurich, which combines slipforming, robotic fabrication processes and concrete material science (Ena, 2016). This technique aims at removing the need of individually made formwork for the construction of complex concrete structures (Gramazio Kohler Research, 2015). The main advantages are the integration of reinforcement during production and no cold joints formation (Wangler, et al., 2016).



Figure 5 Prefabrication with Smart Dynamic Casting (Gramazio Kohler Research, 2015)

CASE STUDY

As presented above, a number of 3D printing techniques are available as alternative construction methods. These technologies aim to revolutionize the construction industry over the next few decades. A comparison between the traditional construction method employed in New Zealand and 3D concrete printing is presented here through a case study. The objective is to highlight the benefits and limitations of 3D printing technology in the New Zealand context.

Approach

The traditional construction method and 3D concrete printing are compared using a case study: a 100m² single-story house, representing a typical 3-person household home in Auckland (see Figure 6). The following criteria are used for the comparison:

- Construction time
- Construction cost
- Other intangible impacts including health and safety of workers, impacts to communities and working precision.

The cost and time of constructing the designed house in the traditional method are analysed based on the Quotable Value Cost Builder (QV costbuilder, 2019), the New Zealand Standard: Thermal Insulation-Housing and Small Buildings (NZS 4218, 2009) and the New Zealand Standard: Timber-framed buildings (NZS 3604, 2011). The project cost estimate for both methods excludes main contractor's preliminaries, margin, contingency and professional fees, which in total account for 17.5% to 19.5% of the total project estimate.

Since there are no 3D printed houses and related standards in New Zealand, the estimation presented in this document, such as the total operation hours of the 3D printer and the cost of 3D printed walls (per square meter), are based on the data obtained from a 3D printed house built by the construction company Apis Cor in 2016 (Apis Cor, 2019). In order to derive the cost of the 3D printed house in New Zealand, replaceable costs obtained from the Apis Cor example (e.g., concrete price and labour costs) are replaced by the local price derived from the New Zealand construction cost information handbook (QV costbuilder, 2019). The Apis Cor's 3D printed house case was selected since it provides elemental costs information and detailed technological information.

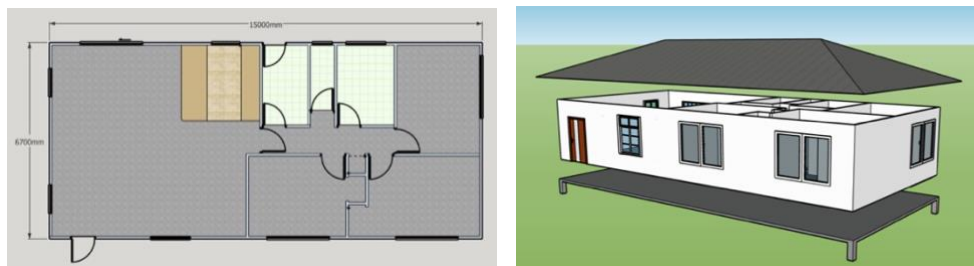


Figure 6 Plan view and 3D model in SketchUp

Traditional construction method analysis

Construction Time

In New Zealand, timber frame is by far the most common structural solution for on-site new houses. A typical house is a timber framed structure with either plaster or brick cladding, a concrete floor slab and a corrugated iron roof. This construction form is environmentally friendly, energy-efficient and flexible.

The construction process and timeline derived using the New Zealand Standard: Timber-framed buildings (NZS 3604, 2011) is summarized in the Gantt chart in Figure 7. The total estimated time for constructing the timber-framed house is 24 weeks. The structural frame and related exterior work take 3 to 4 weeks to complete, and at least 4 workers would be needed. It takes 6 to 7 weeks to complete the wall work and related finishes, which could be a contributing factor for the high estimated cost.

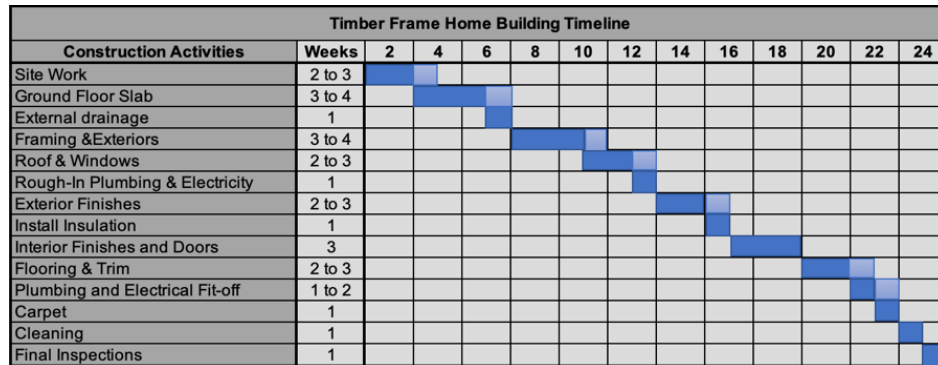


Figure 7 Building timeline of timber frame house

Construction Cost

As shown in Table 2, the total estimated price for the timber framed house is NZ\$255,512.96, of which NZ\$31,860.09 is the extra labour cost that is not included in the material rate. The wall construction and related finishes (NZ\$98,586.53) account for the largest overall percentage of the project estimate (38.6%). The structure work (24.9%) comes next, which includes site preparation, foundation construction and framing. The cost of the roof and ceiling finishes is NZ\$32,811.80, which has the third largest percentage (12.8%).

Table 2 Timber framing project estimate

Project Estimate	Unit	Total Hours	Quantity	Material Rate (\$)	Value	Percentage
Project Details						
Total Floor Area (GFA)	m2		100.00			
Elemental Costs of Buildings						
Structure					63630.33	24.9%
Site Preparation	m2		100.00	22.75	2275.00	
Substructure	m2		100.00	192.50	19250.00	
Frame	m2		437.46	96.25	42105.33	
Walls and Wall Finishes					98586.53	38.6%
Exterior Walls	m2	406.11	271.95	148.03	40257.67	
Internal Walls (Insulation, Linings & Painting)	m2	283.36	783.65	37.22	29164.14	
Roof and Ceiling					32811.80	12.8%
Roof Finishes	m2		142.40	138.25	19686.80	
Ceiling Finishes	m2		100.00	131.25	13125.00	
Windows and Exterior Doors					14281.86	5.6%
Aluminium Windows	m2		22.53	562.00	12661.86	
Entrance Door	no		1.00	1620.00	1620.00	
Interior Doors		46.72	8.00	1300.00	12376.26	4.8%
Floor Finishes					7456.18	2.9%
Carpet	m2		78.73	58.00	4566.34	
Tiles	m2	17.00	15.18	143.00	2170.74	
Fittings and Fixtures			100.00	112.00	11200.00	4.4%
Services					15170.00	5.9%
Sanitary Plumbing	m2		100.00	89.25	8925.00	
Electrical Services	m2		100.00	43.20	4320.00	
Drainage	m2		100.00	19.25	1925.00	
Subtotal		753.19			223652.87	
Labour Cost					753.19* \$42.30 = 31860.09	
				Total	255512.96	

3D concrete printing technology

The Case of Apis Cor

In 2016, the Russian company Apis Cor printed the first on-site house in Moscow at temperatures around -35 °C (Apis Cor, 2019). This is a 38m² odd-shaped house, with a high durable flat roof, a concrete foundation, innovative insulation systems and windows with climate control (see Figure 8). The printing of self-bearing walls, partitions and building envelope was completed in less than a day with the total building cost of US\$10,134. A detailed list of costs, according to the company's website (Apis Cor, 2019), is summarized here:

- Traditional fabricated foundation: US\$277
- Printed Walls: US\$1624 (US\$27/m²)
- Floor and roof: US\$2434
- Wiring: US\$242
- Windows and doors: US\$3548
- Exterior finishing: US\$831
- Interior finishing (including suspended ceiling): US\$1178



Figure 8 Apis Cor printed the first on-site house in Russia (Apis Cor, 2019)

Every 3D construction company has their own distinctive printing system, for example, the BigDelta 3D printing system for the Italian company WASP (WASP, 2019) and the large-scale 3D printing systems for the company XtreeE (XtreeE, 2019). The Apis Cor's printing system consists of a mobile 3D printer, an automated Mobile Automated mix and supply unit (MAU) (Apis Cor, 2019). The company uses this system to print out the house's concrete walls, partitions and building envelope. Then, workers had to manually paint it and install the roofing materials, wiring, hydro-acoustic and thermal insulation. The printing concrete consists of a common sand-cement mixture with specific additives to accelerate setting strength of the mixture and increase its viscosity (Apis Cor, 2019).

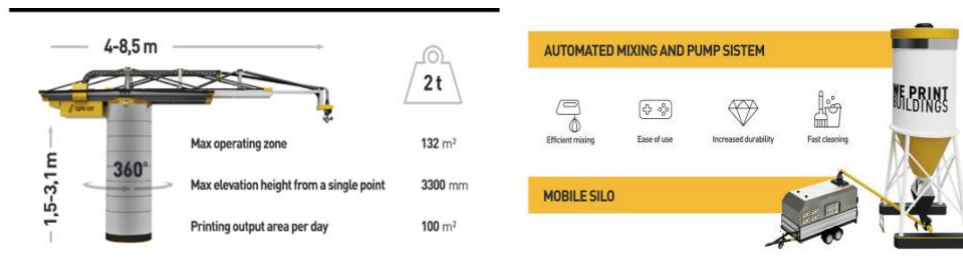


Figure 9 Apis Cor's 3D printing system (Apis Cor, 2019)

Tensile strength and ductility of the structural walls are obtained by including horizontal fiberglass reinforcement in the cavity between the external concrete printed layers (see Figure 10). The internal cavity is filled by spraying a polyurethane-based mixture that works as thermal insulation. The printed walls are finished with a mineral decorative plaster, composed of white cement, marble and granite crumbs (Apis Cor, 2019). The plaster acts as a top layer of thermal insulation.



Figure 10 Printed walls with fiberglass reinforcements and polyurethane composition (Apis Cor, 2019)

Construction Time

The construction process of a 3D printed house differs from the traditional construction method in the fabrication of the structural walls and envelope. So far, no company has been able to print a whole house, but only the walls. The walls can be printed onsite without using formwork, as opposed to buildings being assembled from pre-printed panels. A Gantt chart is presented in Figure 11. The typical work-flow for 3D printing of the walls is shown below (Hager, Golonka, & Putanowicz, 2016):

- A 3D BIM (Building Information Modeling) model is created.
- The BIM model is converted into a STL (Stereolithography Language) file readable by the 3D printer. The STL file format is the standard data transmission format that is used by most Rapid Manufacturing machines.
- In a STL file, the digital model is sliced into numerous cross-sectional material layers with the desired thickness.
- The resulted layers are sent to the 3D printer in a machine-readable language and further processed to generate control commands to position the printing head or laser beams of the 3D printer.
- The walls and the envelope are printed on the concrete slab, and fiberglass reinforcement, piping works and electrical wiring are added manually during the printing process. The roof, the insulations and the windows are installed after the wall is printed.

The construction duration is proportional to the construction expense. The 3D printing technique requires 17.6 weeks to complete the whole process, 6.4 weeks faster than the traditional construction method. The main time saving starts from the 7th week, where the wall printing begins:

- It only takes 72 hours/0.6 weeks (based on the estimate of the Apis Cor case) to print the wall. This is approximately 3 weeks saving compared to the timber framed walls.
- The printed components are integrated with the piping works for HVAC and electrical wiring, thus a minimum of installation is required.
- The exterior and interior wall finishes could be performed immediately after printing and only a decorative plaster and painting are applied, where saved at least 4 weeks.

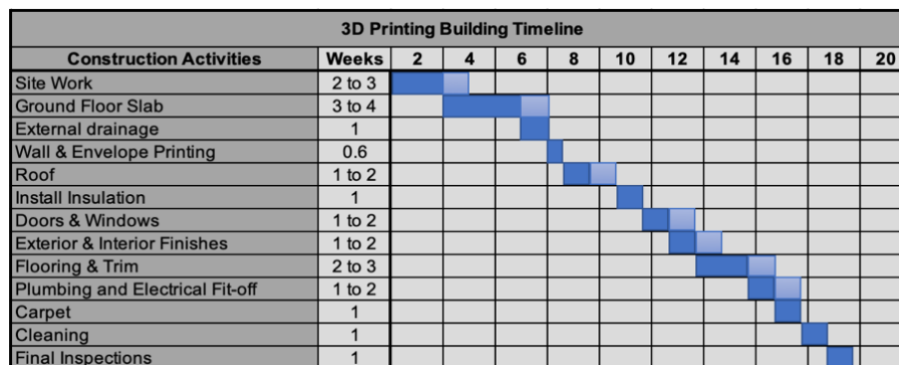


Figure 11 Bulling timeline of 3D printed house

Construction cost

The percentage of the elemental estimate of the 3D construction differs greatly from that of the traditional construction method (see Table 3). Firstly, the roof and ceiling work accounts for the highest overall percentage of the project estimate (29.3%), with a value of NZ\$56,142.80. The cost of roof and ceiling finishes is the same in both methods, the only difference is the addition of the roof and ceiling framework in the 3D printing construction. The wall printing and related finishes hold the second-highest percentage of 27.9%, which has dropped by 10.6% compared with traditional construction methods. Since the wall printing process is completely automatable, only 2 operators are involved to set up the machine, top up materials and

occasionally check. The labour cost is significantly reduced. There is a 13.7% saving on the cost of the structures when the 3D printing technology is employed. This is mainly due to the reduction of timber frame construction. The total project estimate of 3D construction is NZ\$191,735.56, NZ\$63,777.40 (25.0%) lower than the traditional construction.

Table 3 3D construction project estimate

Project Estimate	Unit	Total Hours	Quantity	Material Rate (\$)	Value	Percentage
Project Details						
Total Floor Area (GFA)	m2		100.00			
Elemental Costs of Building						
Structure					21525.00	11.2%
Site Preparation	m2		100.00	22.75	2275.00	
Substructure	m2		100.00	192.50	19250.00	
Walls and Wall Finishes					53583.40	27.9%
Self-Bearing Walls & Building Envelope Printing	m2	72.00	308.00	32.99	10160.92	
Wall Insulation						
- Liquid Polyurethane Composition	m2		167.65	8.94	1498.79	
- LOGICRPIR hard polystyrene	m2		90.65	13.63	1235.56	
Plaster	m2	206.36	308.00	62.00	19096.00	
Wall Painting	m2	77.00	308.00	21.30	6560.40	
Roof and Ceiling					56142.80	29.3%
Frame	m2		242.40	96.25	23331.00	
Roof Finishes	m2		142.40	138.25	19686.80	
Ceiling Finishes	m2		100.00	131.25	13125.00	
Windows and Exterior Doors					14281.86	7.4%
Aluminium Windows	m2		22.53	562.00	12661.86	
Entrance Door	no		1.00	1620.00	1620.00	
Interior Doors	no	46.72	8.00	1300.00	12376.26	6.5%
Floor Finishes					7456.25	3.9%
Carpet	m2		78.73	58.00	4566.34	
Tiles	m2	17.00	15.18	143.00	2170.74	
Fittings and Fixtures	m2		100.00	112.00	11200.00	5.8%
Services					15170.00	7.9%
Electrical Services	m2		100.00	43.20	4320.00	
Sanitary Plumbing	m2		100.00	89.25	8925.00	
Drainage	m2		100.00	19.25	1925.00	
Subtotal		419.08			174008.41	
Labour Cost				746.12 * \$42.30 =	17727.15	
				Total	191735.56	

Other intangible impacts

Besides the tangible aspects, the intangible aspects are also important factors for considering future and innovative construction methods. By introducing 3D concrete printing technology, the interference of construction noise to neighbours is reduced, the health and safety for workers is easily and effectively monitored, as a consequence, medical treatment and ACC cover costs for construction workers may be reduced (Burgess, Buckett, & Page, 2013). Precision can also be improved with increased levels of automation, and thus the quality of the product can be controlled (Burgess, Buckett, & Page, 2013).

DISCUSSION AND FUTURE PROSPECTS

In this paper, the 3D concrete printing technology was discussed as a promising alternative construction method to address the housing crisis in New Zealand. The comparison showed that, by employing 3D concrete printing, the time, cost and manpower can be saved. However, this study is subject to few limitations. The total operation hours and printed wall cost estimates for the 3D concrete printing project were based on the Apis Cor case. In reality, the actual printing time and cost may vary. Also, the labor cost of 3D concrete printing operators may be higher. In this case study, the hourly rate was calculated at the New Zealand average salary as there are no 3D operator wages to be used as a reference. The upfront investments such as purchasing the 3D printing system and the 3D operators training are not included in the cost estimate. More studies are required to investigate the initial investment and the return of the 3D concrete printing technology in the New Zealand context.

The 3D concrete printing technology is still in its infancy and there are various related challenges yet to be solved. At this stage, lack of ductility of the printed elements is an issue since steel reinforcement is not yet fully integrated. Due to the NZ seismic risk, this issue requires further investigation. Also, building services such as electrical and plumbing are not integrated in the printing process, causing issues to the structural integrity. Integration between printed elements and services requires more research. Although there are many 3D concrete printing technologies worldwide, only limited printable materials have been used and some of them are proprietary. Printing materials obtained from local resources should be developed to further reduce construction costs and environmental impacts. The thermal and acoustic properties of the printed elements should be investigated to adapt to the climate and weather in New Zealand.

On the other hand, standards for the management and use of 3D concrete printing should be created before importing this technology to New Zealand. The introduction of this technology into New Zealand's housing market will also require new digital design workflows. Several recent studies focused on the Building Information Modelling (BIM) based 3D printing, which can further help to reduce design coordination errors, more energy-efficient design solutions and faster cost estimation.

Currently, New Zealand is lagging behind other countries in developing 3D concrete printing technology. However, it has attracted lots of attention among researchers, innovators and industry professionals in recent years. Ongoing research is conducted at Callaghan innovation (Jia & Lendrum, 2017). Callaghan Innovation is working on 3D concrete printing system and expected to print the first 3D concrete building in New Zealand within three years.

CONCLUSION

This paper provided an up-to-date review of 3D concrete printing technologies and identified opportunities and limitations of importing the technology into the New Zealand housing sector.

Preliminary results suggest that opportunities include:

- Reduced cost.
- Faster construction time.
- Reduced/diversified labour involvement.
- Automation of the construction process reduces significantly the risk of human error.
- Other intangible advantages such as reduced interference of construction noise to neighbours, minimised hazards to workers, improved precision and quality of the product.

Current limitations include:

- The need to improve the structural ductility and integrity properties.
- The need to investigate and develop local printing and insulation materials.
- The lack of standards of 3D concrete printing.
- The need to develop new digital design workflows for the industry.

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Reference

- Apis Cor. (2018). What is construction 3D printing: perspectives and challenges. Retrieved from Apis Cor: <https://www.apis-cor.com/blog>. Accessed May 2019.
- Apis Cor. (2019). 3D printing a home for under USD\$10,000. Retrieved from Apis Cor: <https://www.apis-cor.com/library>. Accessed March 2019.
- Buckett, N. (2013). Advanced Residential Construction Techniques for New Zealand. BRANZ.
- Burgess, J., Buckett, N., & Page, I. (2013). Prefabrication Impacts in the New Zealand Construction Industry. BRANZ.
- Chua, C. K., & Leong, K. F. (2017). In 3D printing and additive manufacturing: principles and applications (pp. 291-293). Singapore: World Scientific.
- CyBe. (2019). 3D concrete printers. Retrieved from CyBe: <https://cybe.eu/3d-concrete-printers/>. Accessed July 2019.
- D-shape. (2019). What is D-shape? Retrieved from D-shape: <https://d-shape.com/the-vision/>. Accessed March 2019.
- D-Shape. (2010). Una Casa Tutta DiUn Pezzo. Retrieved from <https://d-shape.com/portfolio-item/casa-ferreri/>. Accessed April 2019.
- Ena, L. (2016). Smart Dynamic Casting - A digital fabrication method for non- standard concrete structures. ETH Zurich, Switzerland.
- Gramazio Kohler Research. (2015). Smart Dynamic Casting. Retrieved from ETH Zurich: <http://gramaziokohler.arch.ethz.ch/web/e/forschung/325.html>. Accessed April 2019.
- Gramazio Kohler Research. (2018). Mesh Mould Metal. Retrieved from <http://gramaziokohler.arch.ethz.ch/web/e/forschung/316.html>. Accessed April 2019.
- Hack, N., Wangler, T., Mata-Falcón, J., Dörfler, K., Kumar, N., Walzer, A. N., . . . Kohler, M. (2017). Mesh mould: an on site, robotically fabricated, functional formwork. Second Concrete Innovation Conference (2nd CIC).
- Hager, I., Golonka, A., & Putanowicz, R. (2016). 3D printing of buildings and building components as the future of sustainable construction? *Procedia Engineering* 151, pp. 292-299.
- Jia, Y., & Lendrum, C. (2017). 3D Printing Of Concrete: Opportunities And Challenges. *The New Zealand Concrete Industry Conference*.
- Johnson, A. (2018). A Stocktake of New Zealand's Housing. New Zealand Government.
- Khoshnevis, B. (2004). Automated construction by contour crafting—related robotics and information technologies. *Automation in Construction*, pp. 5-19.
- Khoshnevis, B., Russell, R., Kwon, H., & Bukkapatnam, S. (2001). Contour crafting—a layered fabrication technique. *Special Issue of IEEE Robotics and Automation Magazine*, pp. 33-42.

- Lim, S., Buswell, R., Valentine, P., Piker, D., Austin, S., & De Kestelier, X. (2016). Modelling curved-layered printing paths for fabricating large-scale construction components. *Additive Manufacturing*, pp. 216-230.
- Lim, S., Buswell, R. A., Le, T. T., Wackrow, R., Austin, S. A., Gibb, A. G., & Thorpe, T. (2011). Development of a viable concrete printing process.
- Lim, S., Le, T., Webster, J., Buswell, R., Austin, S., Gibb, A., & Thorpe, T. (2009). Fabricating construction components using layer manufacturing technology. *Loughborough University*, pp. 13-16.
- Loughborough University. (2019). 3D Concrete Printing. Retrieved from Loughborough University: <https://www.lboro.ac.uk/enterprise/3dcp/>. Accessed April 2019.
- Ministry of Business, Innovation & Employment. (2017). Briefing for the Incoming Minister of Housing & Urban Development.
- NZS 3604. (2011). New Zealand Standard: Timber-framed buildings.
- NZS 4218. (2009). New Zealand Standard: Thermal insulation - Housing and small buildings.
- Panda, B., Bahubalendruni, R., Biswal, B., & Leite, M. (2017). A CAD-based approach for measuring volumetric error in layered manufacturing. *Proceedings of the Institution of Mechanical Engineers*, pp. 2398-2406.
- QV costbuilder. (2019). Retrieved from <https://qvcostbuilder.co.nz/app.html#/home/book/page-id/c4549c0e-b9f6-42cb-81d5-c707df94135f>. Accessed July 2019.
- Richardson, V. (2017). 3D printing becomes concrete: exploring the structural potential of concrete 3D printing. *The Structural Engineer*, 95(10): 10-17.
- Stats NZ. (2019). Stats NZ. Retrieved from <http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE7541#>. Accessed June 2019.
- Tay, Y., Panda, B., Paul, S., Noor Mohamed, N., Tan, M., & Leong, K. (2017). 3D printing trends in building and construction industry: a review. *Virtual and Physical Prototyping*, pp. 261-276.
- Wangler, T., Lloret, E., Reiter, L., Hack, N., Gramazio, F., Kohler, M., . . . Flatt, R. (2016). Digital Concrete: Opportunities and Challenges. *RILEM Technical Letters*, pp. 67-75.
- WASP. (2019). 3D printers. Retrieved from WASP: <https://www.3dwasp.com/en/delta-3d-printer-delta-wasp-2040-pro/>. Accessed July 2019.
- XtreeE. (2019). Retrieved from <https://www.xtreee.eu>. Accessed July 2019.